NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4254

FLIGHT INVESTIGATION OF EFFECTS OF RETREATING-BLADE STALL ON BENDING AND TORSIONAL MOMENTS ENCOUNTERED BY A HELICOPTER ROTOR BLADE

By LeRoy H. Ludi

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

Flight tests have been conducted with a medium-size single-rotor helicopter, one blade of which was equipped with strain gages, to determine the effects of retreating-blade stall on the rotor blade bending and torsional moments during high-speed flight and pull-up maneuvers.

The results indicate that retreating-blade stall has a substantial effect on the periodic rotor blade moments. In the stalled condition, the higher harmonics can become almost as large numerically and as important from a fatigue standpoint as the lower harmonics. Since these increased moments, particularly the torsional moments, cause increased periodic control loads and increased vibration in the helicopter control system, they may tend to restrict the normal operating limits of future high-performance helicopters unless an adequate combination of means to reduce these moments and means to design for their fatigue effects is devised.

INTRODUCTION

A key item in obtaining increased reliability, reduced maintenance time, and reduced overall cost of helicopters, together with light structural weight, is the designing of the various components to avoid fatigue failures. Periodic moments in the rotor blade and the resultant loads in the control systems can lead to failure of these very critical parts unless they are designed to withstand their cumulative effects. Currently, the helicopter industry has encountered increased periodic control loads in high-performance prototype helicopters during high-speed flight and especially during high-speed maneuvers. These increased loads have seriously restricted the normal operating limits of these prototypes and are a matter of great concern.

The increased periodic control loads are a result of increased torsional moments about a spanwise axis. These increased torsional moments are not as critical as the bending moments in determining the fatigue life of the blade itself, but they are of prime importance in the control-system design. Since the results presented in reference 1 have shown that atmospheric turbulence and moderate control motions contribute little to the total torsional and bending moments, retreating-blade stall was suspected of being a primary cause of these increased moments in high-speed level flight and high-speed maneuvers. Reference 2 indicates that stalling imposes a practical limit on the condition of operation that may be utilized. In the investigation of reference 3, the performance losses due to stalling began about as tip stalling set in. In an effort to obtain further insight into effects of retreating-blade stall on the rotor blade moments, tests were conducted with the strain-gage-equipped, single-rotor helicopter described in reference 1. The results of the investigation are presented herein.

To determine the effects of stall, the results of two flight conditions which produce increased amounts of stall were examined in more detail. They were high-speed level flight and pull-up maneuvers. In both conditions, retreating tip angles of attack as high as 6° or 7° beyond the stall value were encountered. The results of this investigation should provide some insight into the problem of increased periodic control loads in future helicopters during high-speed level flight and high-speed maneuvers.

SYMBOLS

a_n normal acceleration, g units

$\alpha_{(1.0)(270^{\circ})}$ blade-element angle of attack at tip of retreating blade at 270° azimuth position, deg

μ tip-speed ratio, $\frac{V \cos \alpha}{\Omega R}$

V true airspeed, ft/sec

α rotor angle of attack, radians

Ω rotor angular velocity, radians/second

R blade radius, ft

C_T thrust coefficient, $\frac{T}{\pi R^2 \rho (\Omega R)^2}$

T rotor thrust, Wa_n, lb

ρ mass density of air, slugs/cu ft

W helicopter weight, lb

APPARATUS

The single-rotor helicopter used in the investigation is shown in figure 1, and its principal dimensions and approximate physical characteristics are given in reference 1. The helicopter has conventional pilot controls: stick, pedals, and collective-pitch lever. It is equipped with standard NACA recording instruments with synchronized time scales which measure airspeed, altitude, manifold pressure, rotor rotational speed, pilot-control positions, angular velocities about the three principal inertia axes, and center-of-gravity acceleration.

The main rotor blades are of all-metal construction with an NACA 0012 airfoil section and -8° of linear twist (tip pitch lower than root pitch). Each rotor blade is equipped with flapping and drag hinges offset approximately 3 percent of the blade radius. The feathering axis and the chordwise center of gravity of the blade are coincident at 25 percent of the chord. Feathering control of the blades is applied outboard of the flapping and drag hinges.

Resistance-wire strain gages are mounted on the spar of one blade to form complete bridges at 14 percent and 40 percent of the blade radius. The strain gages at the 40-percent-radius station measure only flapwise bending moments, whereas the strain gages at the 14-percent-radius station measure flapwise and chordwise bending and torsional moments. (These moments are hereinafter referred to as 14-percent chordwise bending moments, 40-percent flapwise bending moments, and so forth.)

PROCEDURE

Since rotor blade stall is a function of the tip angle of attack on the retreating blade, two conditions that produce large retreating tip angles of attack were investigated: (1) high-speed steady flight and (2) pull-up maneuvers. Data were obtained for values of thrust coefficient C_T ranging from 0.0041 to 0.0073 and tip-speed ratio μ ranging from 0.14 to 0.36. The selection of forward speed and rotor rotational speed to give the maximum feasible amount of stall for the first condition was left up to the discretion of the pilot. The pull-up maneuvers were executed to obtain the maximum acceleration increment possible, within common-sense limitations, in normal pull-ups from level flight. The methods of reducing the data used in reference 1 were also used in this investigation.

Calculation of Retreating Tip Angle of Attack

Since the retreating tip angle of attack was not actually measured during the tests, it was calculated by means of standard rotor theory (ref. 4) with the assumption of a horsepower loss of 15 percent between the engine output (as determined by engine manifold pressure and rotational speed) and main rotor input. In addition, the effects of dynamic twist (twisting of the blade due to applied loads) on the blade pitch were investigated to determine whether the twist could change the blade angle of attack a significant amount. A static test revealed that a torsional moment of 1,080 inch-pounds at the tip produced a tip-angle change of only 1.2° for the blades used in this investigation. Figure 9 of reference 5 shows that a dynamic twist of approximately $\pm \frac{1}{4}^{\circ}$ was encountered by a tubular-spar fabric-covered rotor blade in flight in a stalled condition at a lower value of μ but at about the same mean lift coefficient as used in the present investigation. Since the torsional stiffness of the blades in this investigation is more than twice the stiffness of the fabric blades, it is reasonable to assume that dynamic blade twist has little effect on the rotor blade stall patterns.

Selection of Stall Angle

Experience with rotors in flight has shown that values under 12° for the retreating tip angle will result in unstalled conditions and values more than 1° or 2° above 12° will result in stalled conditions. Unpublished data obtained with the Langley helicopter test tower on blades that were exact duplicates of those used in the present investigation also showed that a retreating tip angle of slightly more than 12° was a good basis for defining the start of the stalled regime. Although there is some uncertainty about the amount of stall encountered with retreating tip angles between 12° and 14°, the value of 12° was chosen to separate the definitely unstalled region from the stalled region.

RESULTS AND DISCUSSION

Moment records are presented and analyzed in order to show the effects of rotor blade stall on the periodic moments encountered by a helicopter rotor. The moments in the stalled condition are compared with the moments in the unstalled conditions. The results of the harmonic analyses are presented to show the moment increases due to stalling.

Effect of Stall in Steady Forward Flight

Actual traces.- Figure 2 gives representative samples of the actual traces obtained in steady flight during unstalled and stalled conditions. Calculations indicate that a μ value of about 0.24 in steady flight gives a retreating tip angle of attack of 12°. In the figure, two samples of unstalled flight and two samples of stalled flight are shown. The amplitude and harmonic content of the traces are noticeably different for the stalled and unstalled conditions. These traces are presented for illustrative purposes and are analyzed in detail later.

Vibratory moments.- When retreating-blade stall is encountered by the rotor, increased vibratory torsional and bending moments act on the blade. The increased vibratory torsional moments are of prime importance in the design of the control systems, whereas the increased vibratory bending moments are of prime importance in the design of the blade itself. As the retreating tip angle increases above the stall angle of 12°, the stalled area spreads over more and more of the retreating blade and causes more of an increase in these vibratory moments.

This effect of stall on the torsional moments is illustrated in figure 3. In this figure, the torsional moments at various tip-speed ratios are divided by the torsional moments at the tip-speed ratio which first produced a retreating tip angle of 12° and plotted against μ. The open symbols represent unstalled conditions and the solid symbols represent stalled conditions. It can be seen that the moments increase at a fairly shallow rate until the retreating tip angle of attack exceeds the stall angle; then they increase rapidly. The ratios of torsional moments are fairly small when the retreating tip angle exceeds the stall angle by only 1° or 2° ($\mu = 0.26$ and $\mu = 0.28$). However, when the retreating tip angle exceeds the stall angle by more than 3° or 4° ($\mu = 0.30$ to 0.36) the ratios increase rapidly to a value of almost 3. This result indicates that large amounts of stall can cause large increases in the blade torsional moments. The increase in the ratio to a value of 3 results in an absolute increase in the vibratory torsional moments of more than 2,300 inch-pounds. These increased vibratory torsional moments must be given careful consideration in the design of control systems in order to avoid fatigue failures.

The effects of rotor blade stall on the flapwise and chordwise vibratory bending moments are shown in figure 4. In this figure, the respective moments at the various values of μ are divided by the respective moment at $\mu = 0.24$ and plotted against μ. All three curves show little change until μ exceeds a value of 0.24, at which time $\alpha_{(1.0)(270^{\circ})}$ exceeds 12°. Then, the curve for the 14-percent flapwise bending moment increases rapidly to a maximum ratio of about 3, while the curves for the 40-percent flapwise and 14-percent chordwise bending moments increase at a slower rate and reach a lower maximum. An increase in the ratio to a value of 3 results in an absolute increase in the 14-percent flapwise vibratory bending moment of more than 2,200 inch-pounds. This increase in moment corresponds to a stress increase of more than 1,600 lb/sq in. In combination with the other stresses on the blade, the vibratory stress increase of 1,600 lb/sq in. must be given considerable weight in designing the blades to provide satisfactory fatigue life.

Harmonic analysis of moment records.- The actual traces presented in figure 2 show a definite first-harmonic moment plus moments due to higher harmonics. To determine the harmonic content of the moment traces, 24-point harmonic analyses were performed. Some representative results of these harmonic analyses are presented in figure 5 for three different forward speeds. In all the harmonic-analysis bar graphs, a positive steady-state value indicates (1) for flapwise bending moment, compression in the upper surface of the blade, (2) for chordwise bending moment, compression in the trailing edge of the blade, and (3) for torsional moment, couple tending to rotate the blade leading edge upward. (Negative steady-state moments are indicated by minus signs over the bars.) The first two speeds ($\mu = 0.26$ and 0.28) result in retreating tip angles of attack which are only 1° or 2° beyond the stall angle for the airfoil section. The third and highest speed ($\mu = 0.36$) results in a retreating tip angle which is about 6° or 7° beyond the stall. A comparison of the runs at $\mu = 0.26$ and $\mu = 0.28$ and some unplotted results at lower speeds shows, in general, that there is little difference in the moments encountered by the blade. However, the run at $\mu = 0.36$ shows some outstanding changes. In all graphs except that for the 14-percent chordwise bending moment, large increases are evident in the first and second harmonic moments as a result of the large amount of stall. In addition, the 14-percent torsional moments show an outstanding sixth-harmonic componont. The frequency of this sixth harmonic during the high-speed run is about 19 cycles per second, which is very close to the blade torsional natural frequency of about 20 cycles per second, as shown in figure 8 of reference 1.

Effect of Stall in Pull-Up Maneuvers

Since maneuvers can affect the amount of blade stall, a series of maneuvers, with varying tip angles, was investigated.

Actual traces.- The actual traces obtained during two representative pull-ups are shown in figure 6. In this figure, the traces are shown for a part of the run prior to the maneuver and for the part during the maneuver in which the acceleration is a maximum. Figure 6(a) shows the traces for the case in which the retreating blade is unstalled at the maximum acceleration point, and figure 6(b) shows the traces for the case in which the retreating tip angle of attack exceeds the stall angle by about 6° at the maximum acceleration point. These traces indicate that the increase in vibratory moment is a function of the amount of stall rather than the maximum acceleration.

Vibratory moments.- The effect of pull-up maneuvers on the torsional moments is illustrated in figure 7. The torsion encountered at the maximum acceleration point during the maneuver is divided by the torsion prior to the maneuver and plotted against the maximum acceleration during the maneuver. It can be seen that increased moments are obtained at any given acceleration level as the retreating tip angle of attack exceeds the stall value to a greater extent. The figure also shows indications that the maximum acceleration obtainable, within the pilot's discretion, tends to be reduced when the stall angle is exceeded by 4° to 6°. Torsional moments three to four times the value prior to the maneuver are easily obtained in the highly stalled condition.

The effects of maneuvers on the 14-percent and 40-percent flapwise bending moments and 14-percent chordwise bending moments are shown in figure 8. In this figure the bending moments at the maximum acceleration point are divided by the corresponding bending moments prior to the maneuver and plotted against the maximum acceleration value during the maneuver. The results for the 40-percent flapwise bending and 14-percent chordwise bending moments show little change in the ratio with change in the retreating tip angle of attack. Although there is considerable scatter in the results for the 14-percent flapwise bending moment, in general the highest blade moments were obtained at the highest retreating tip angle of attack. Flapwise moments three to four times as great as those prior to the maneuver are also easily obtained in the highly stalled condition. This scatter is believed to be a result of the variation in other parameters which also affect this station during pull-up maneuvers.

Harmonic analysis of moment records.- In order to illustrate the effect of stall on the individual harmonics at the maximum acceleration point, figure 9 is presented. In this figure the various moments at the different stations are presented for the steady state and first ten harmonics. The moments for two representative maneuvers were obtained at the maximum acceleration point during each maneuver. The unshaded bars represent the moments obtained at $\alpha_{(1.0)(270^{\circ})} = 12^{\circ}$ and an acceleration of 1.66g, whereas the shaded bars represent the moments obtained at $\alpha_{(1.0)(270^{\circ})} = 18^{\circ}$ and an acceleration of 1.52g.

In general, the figure shows a definite effect of stall at all the stations. The increased moments are considered a result of stall rather than of acceleration, since the acceleration in a pull-up maneuver cannot be obtained unless the blade angle of attack is increased. In the highly stalled condition, the higher harmonics take on added significance in the design of rotor blades and rotor control systems.

The results of figure 9 are believed to be representative of the moment increases that would be obtained during maneuvers when retreating-blade stall is encountered. These large amounts of stall are characterized by feedback through the power-boost control and thus tend to limit the maximum acceleration that can be obtained, within common-sense limitations, in a pull-up maneuver. From these results it is evident that retreating-blade stall can also cause large increases in the blade moments during pull-up maneuvers.

CONCLUSIONS

The flight investigation of the effects of retreating-blade stall on the periodic rotor blade moments of a medium-size, fully articulated, single-rotor helicopter indicated the following conclusions:

1. In high-speed steady flight, retreating-blade stall can cause large increases in the periodic moments encountered by a helicopter rotor. The torsional moments in the highly stalled condition are of primary importance in the design of helicopter control systems since they are three times as great as the torsional moments in the unstalled condition. The vibratory bending moments in the highly stalled condition are of primary importance in the design of the rotor blade since they also can be three times as great as in the unstalled condition. These increased moments, particularly the torsional moments, cause increased periodic control loads and increased vibration in the helicopter control system and thereby tend to restrict the high-speed operating limits of future helicopters unless they are carefully considered in the initial design stages.

2. Pull-up maneuvers were found to produce essentially the same results as the high-speed steady-flight condition. In addition, the maximum acceleration obtainable, within the pilot's discretion, in a pull-up maneuver tends to be limited when large amounts of stall are present.

3. In the stalled condition, the higher harmonics must be given as much consideration as the lower harmonics during the design stages of future high-performance helicopters.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 20, 1958.

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Figure 1.- Test helicopter. L-84196

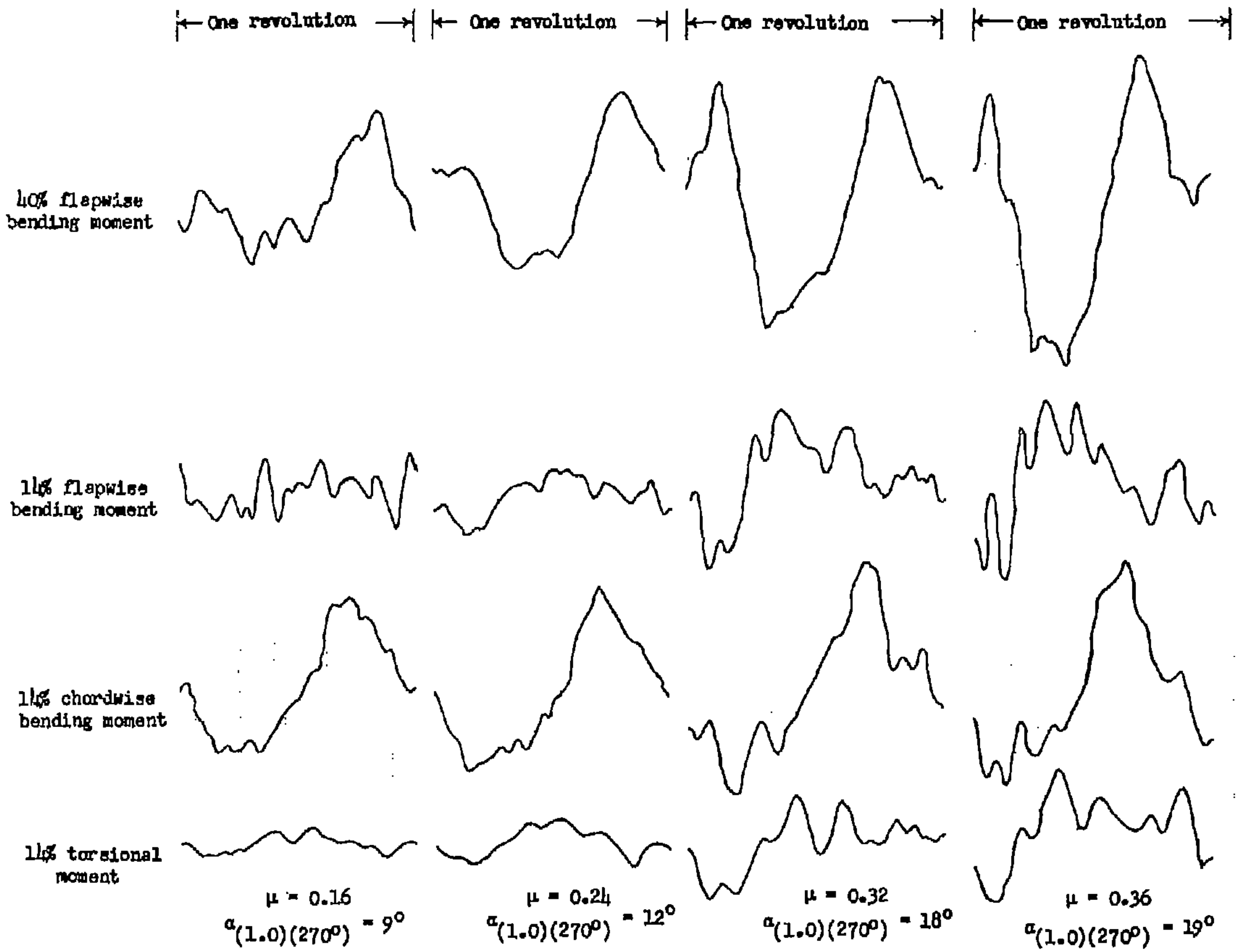


Figure 2.- Typical time histories of rotor blade moments during steady flight at various tip-speed ratios.

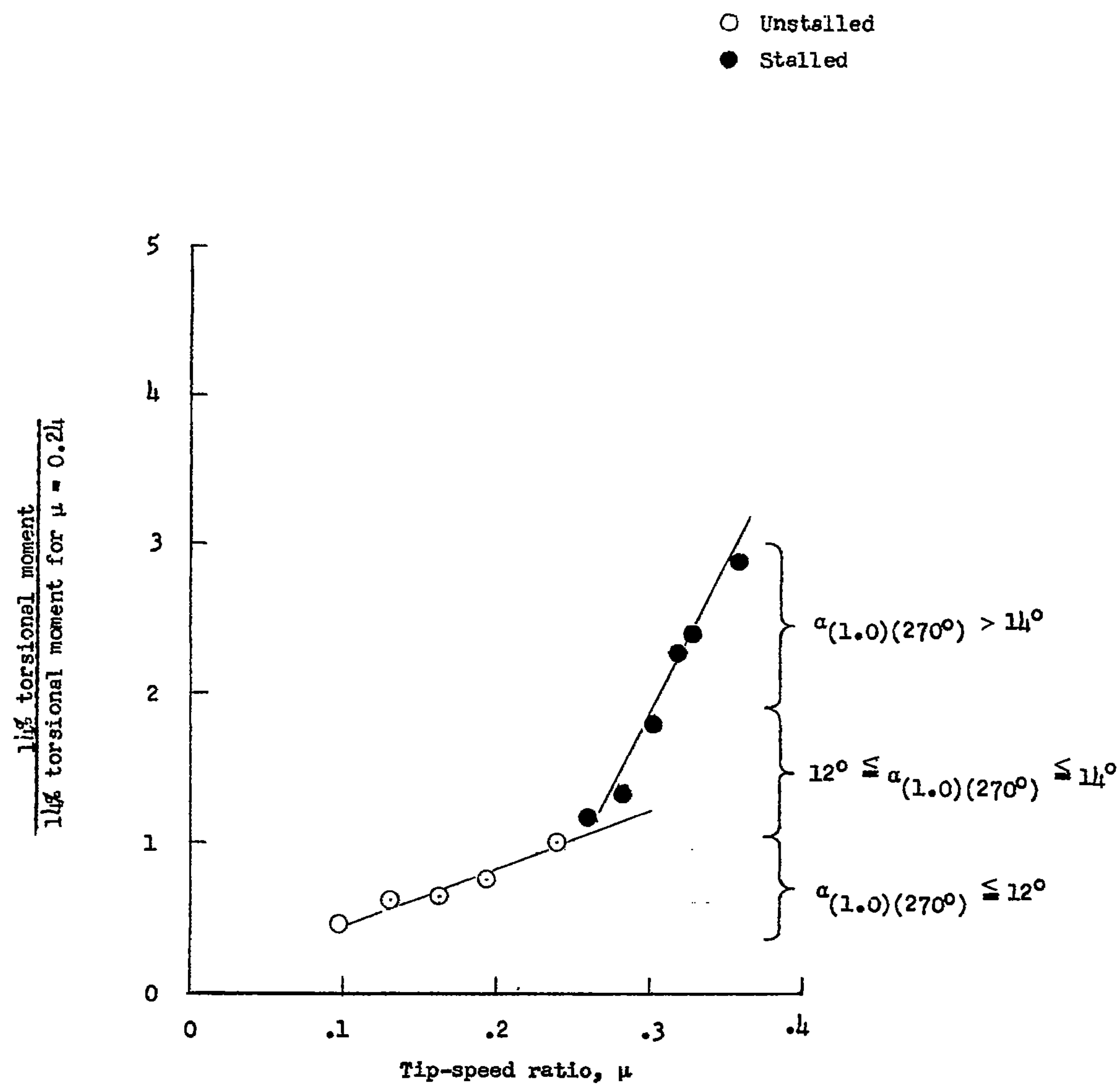


Figure 3.- Vibratory torsional moments as a function of tip-speed ratio for unstalled and stalled steady forward flight.

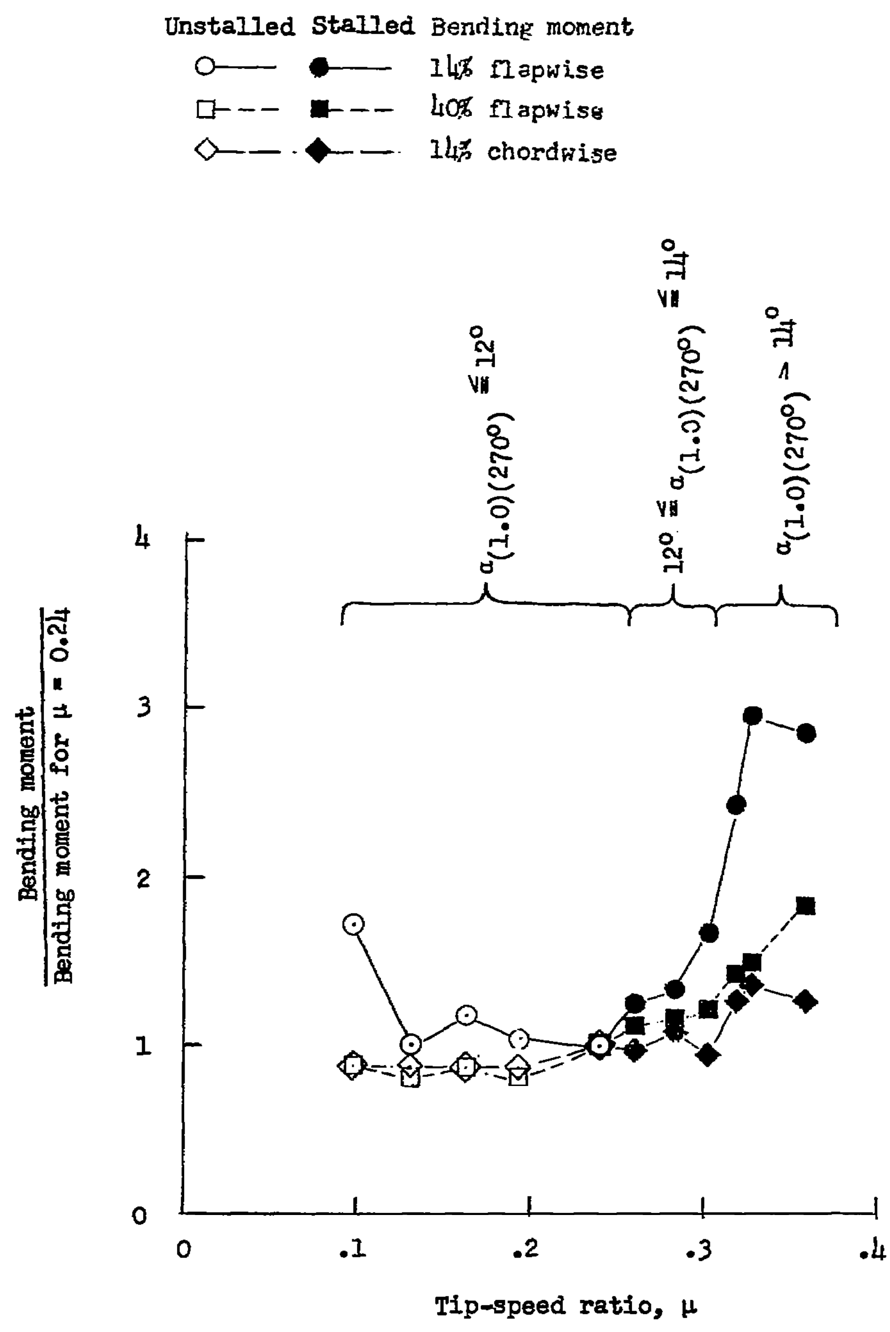


Figure 4.- Vibratory bending moments as a function of tip-speed ratio for unstalled and stalled steady forward flight.

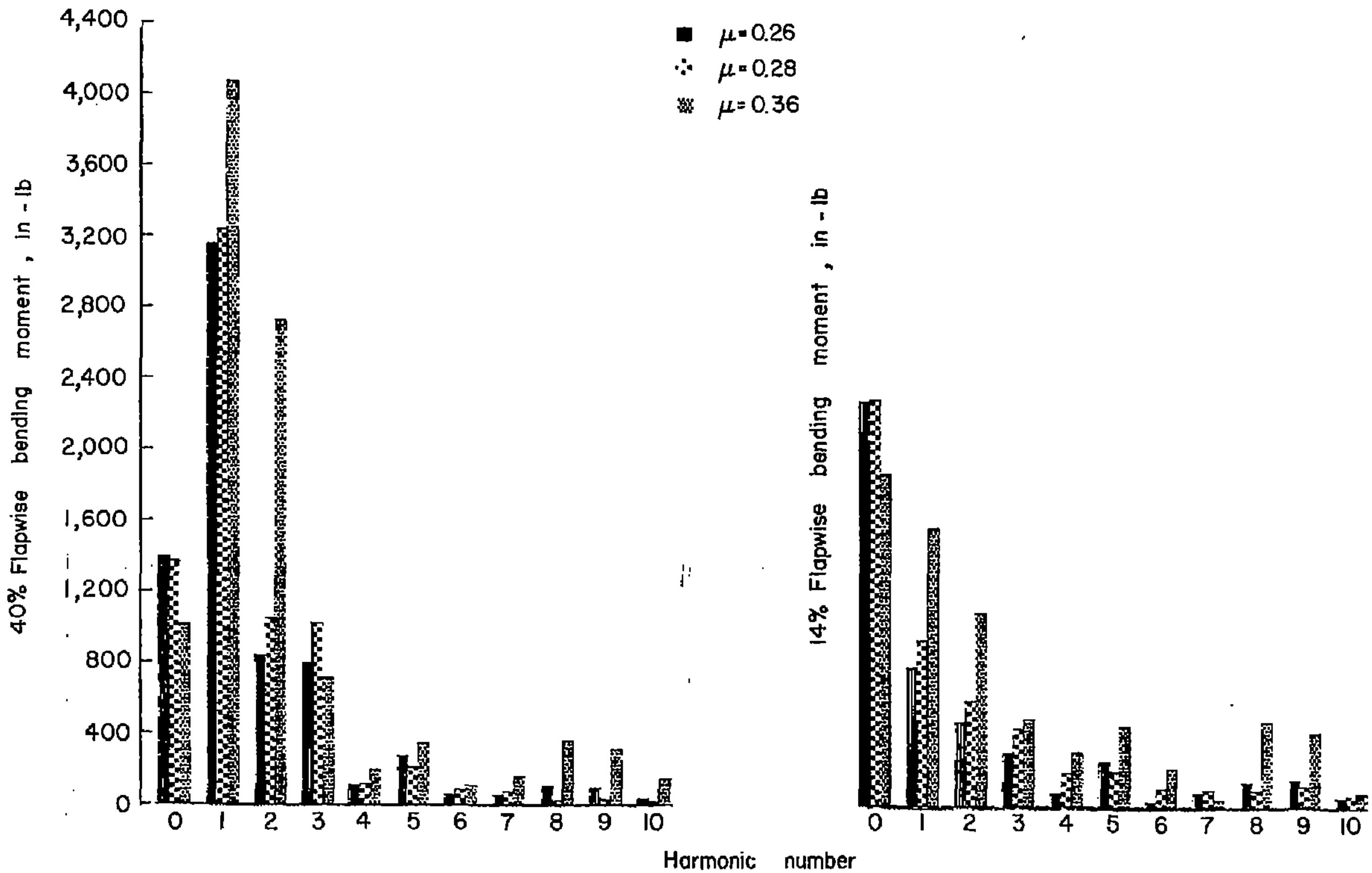


Figure 5.- Effect of retreating-blade stall on rotor blade moments during steady forward flight.

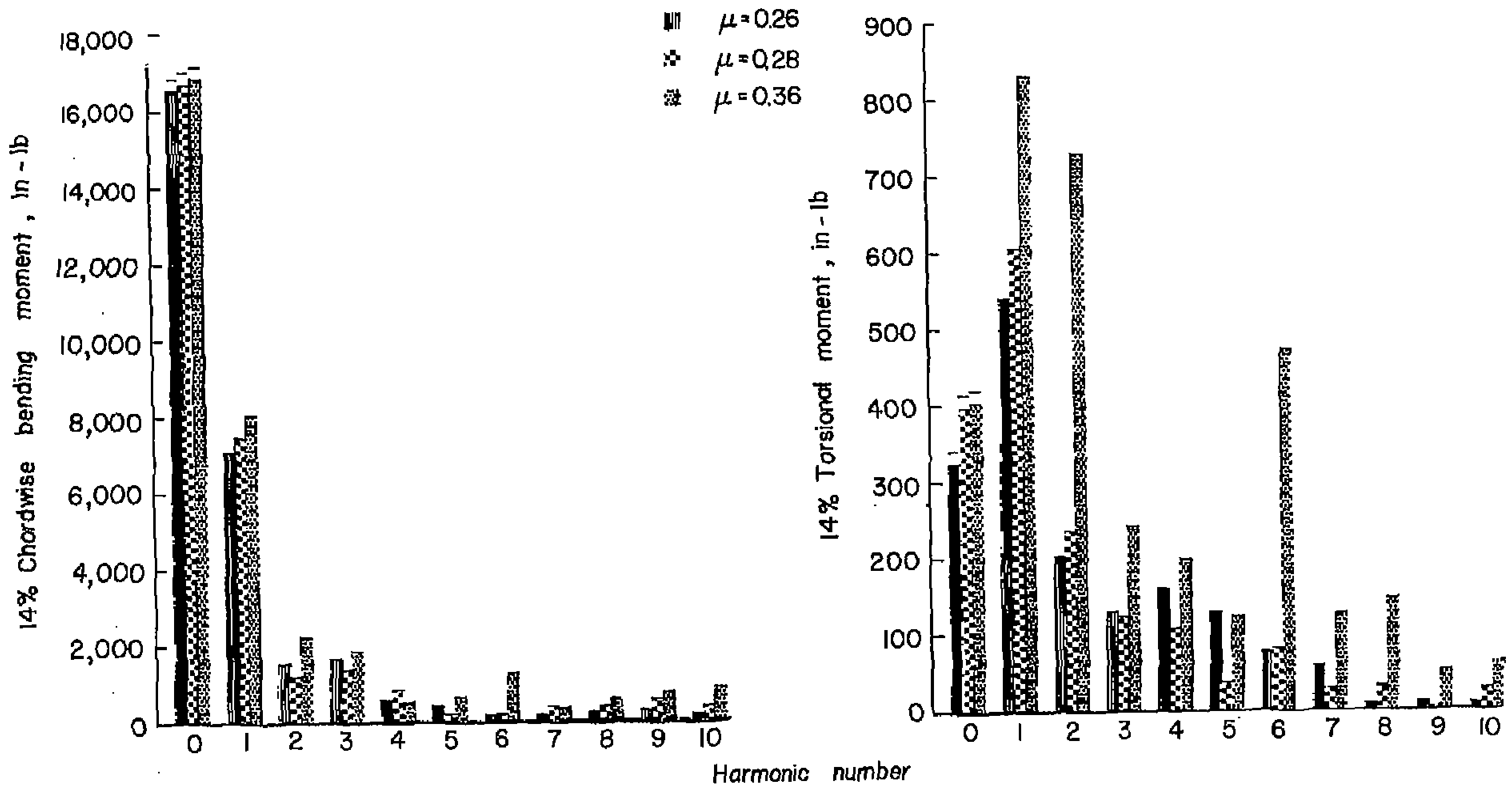
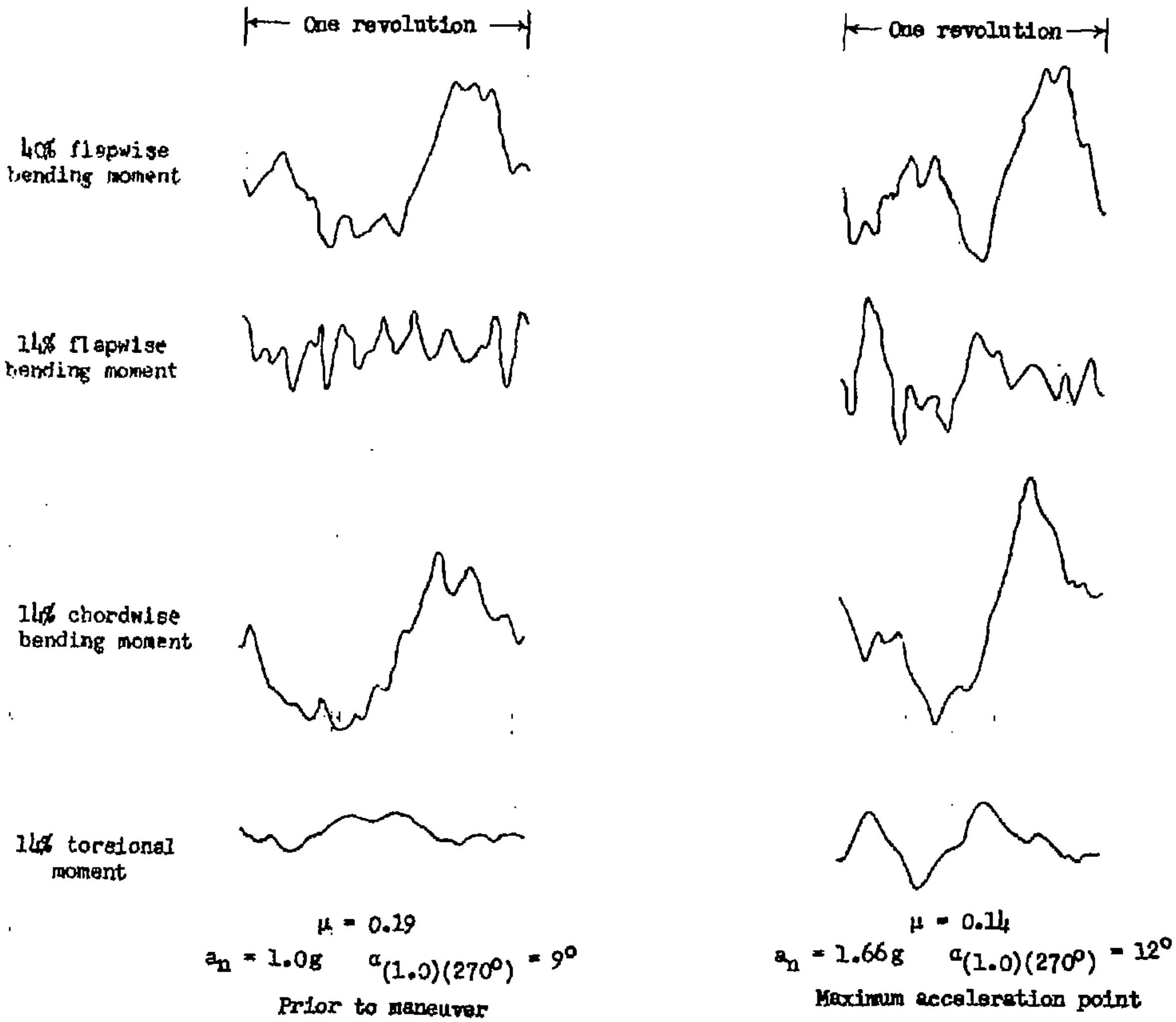
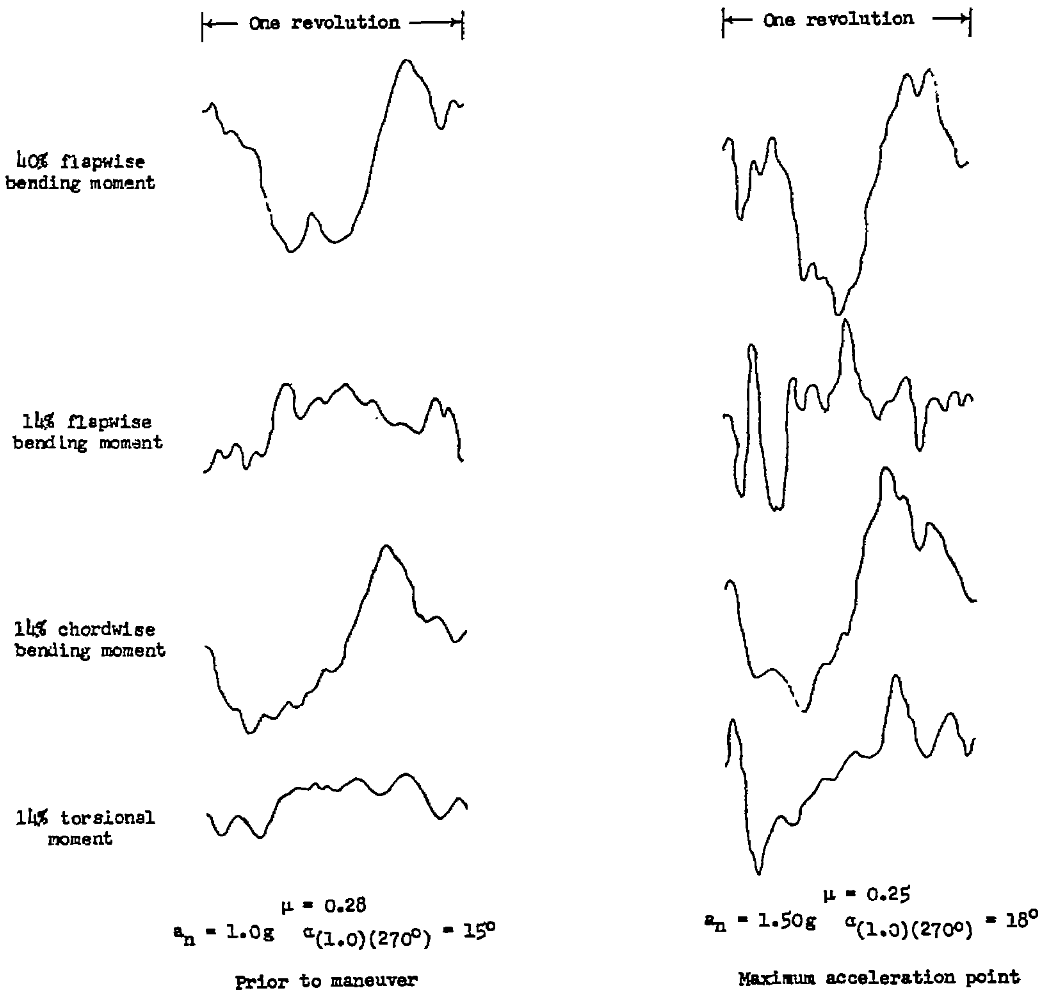


Figure 5.- Concluded.



(a) Retreating tip unstalled.

Figure 6.- Typical time histories of rotor blade moments during pull-up maneuvers.



(b) Retreating tip stalled.

Figure 6.- Concluded.

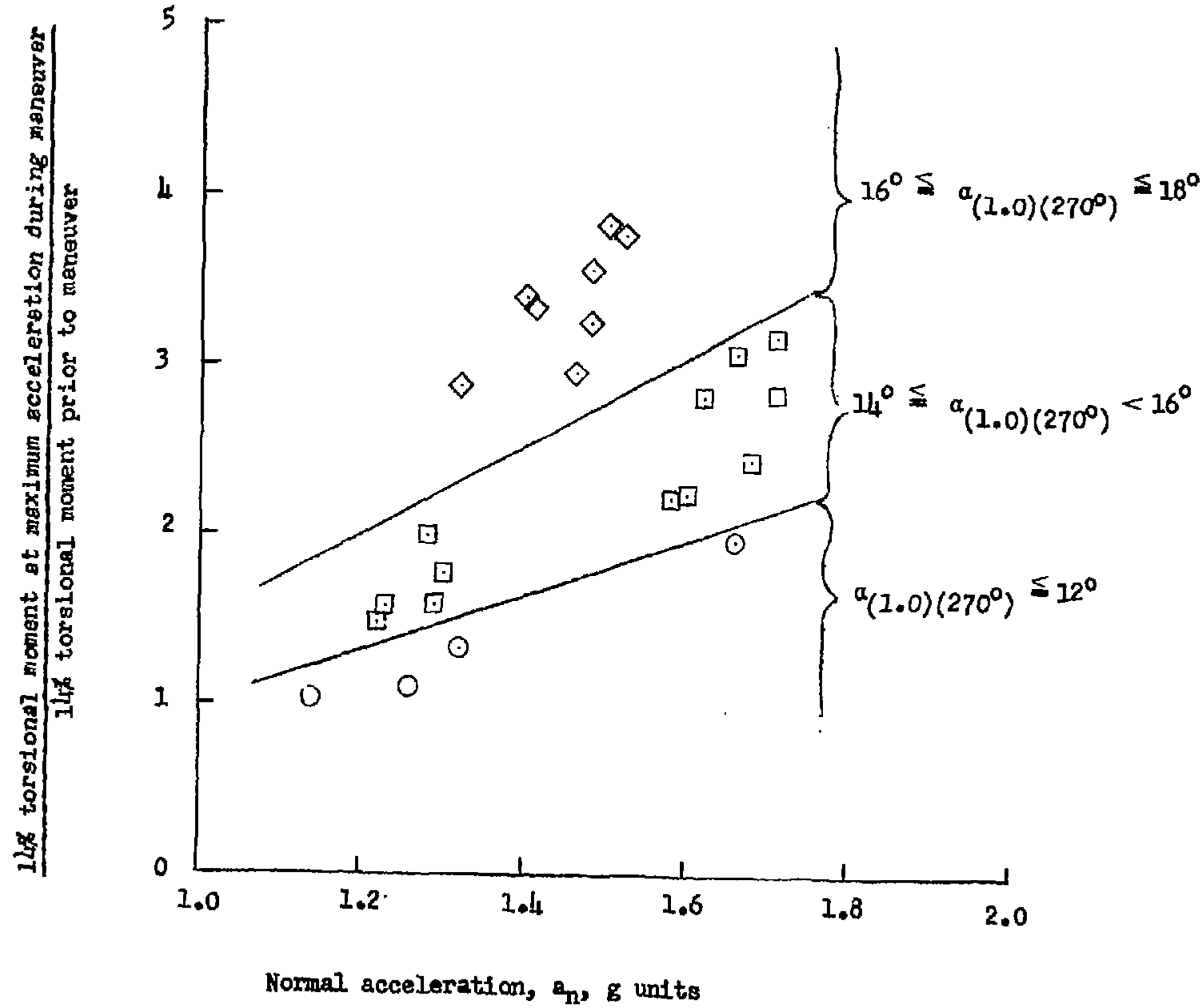


Figure 7.- Vibratory torsional moments as a function of acceleration during pull-up maneuvers.

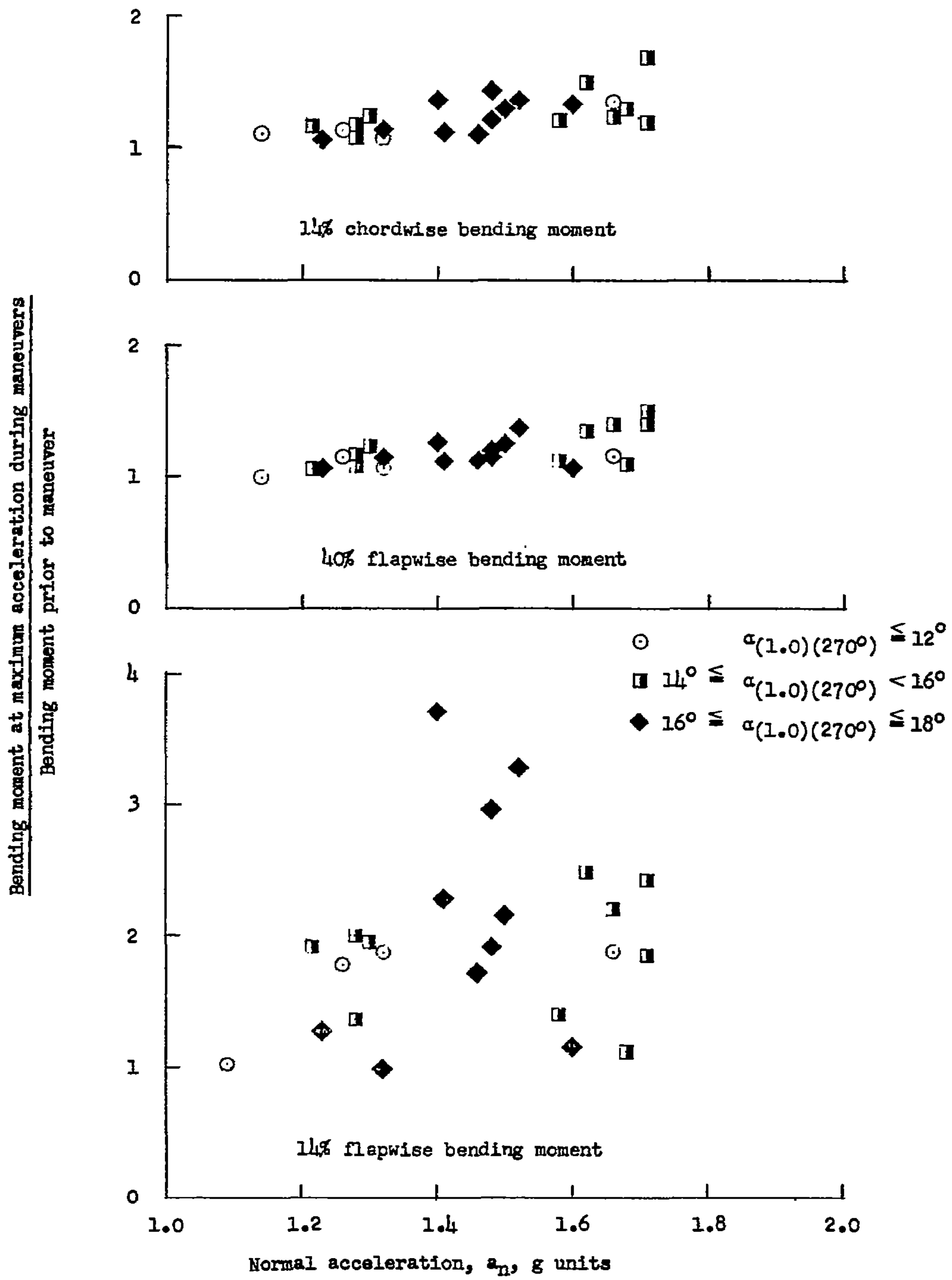


Figure 8.- Vibratory bending moments as a function of acceleration during pull-up maneuvers.

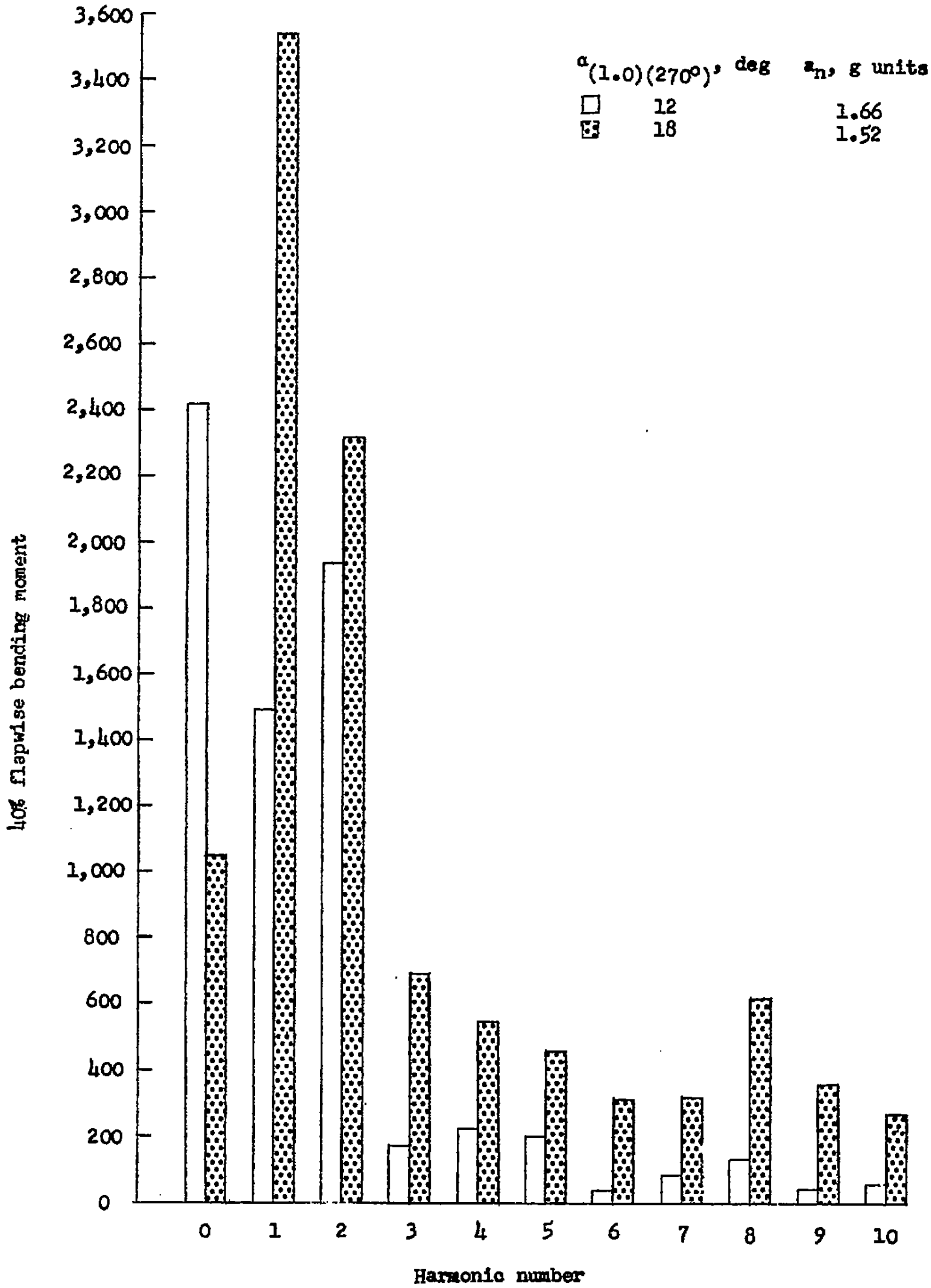


Figure 9.- Effects of retreating-blade stall on rotor blade moments at the maximum acceleration point of two pull-up maneuvers.

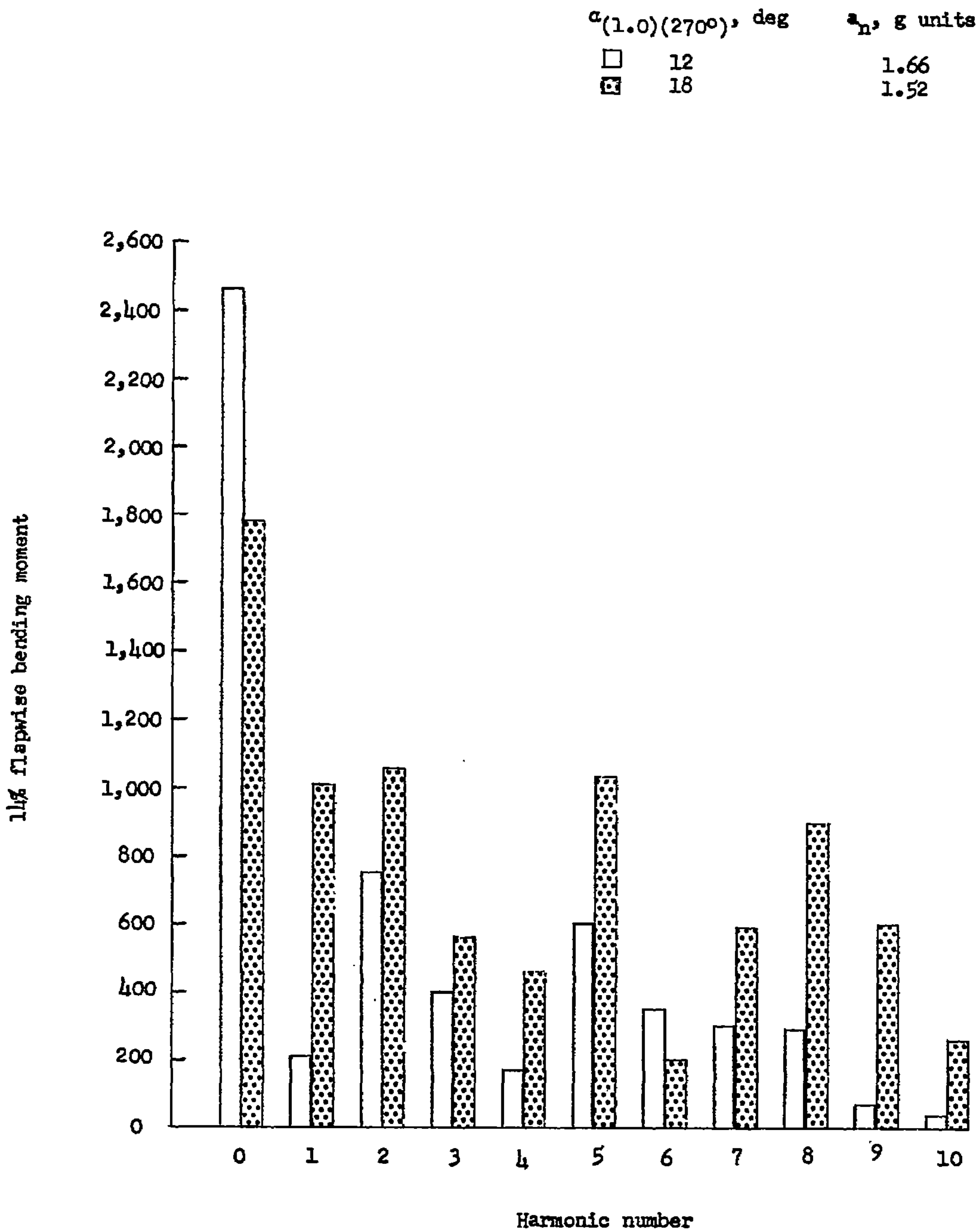


Figure 9.- Continued.

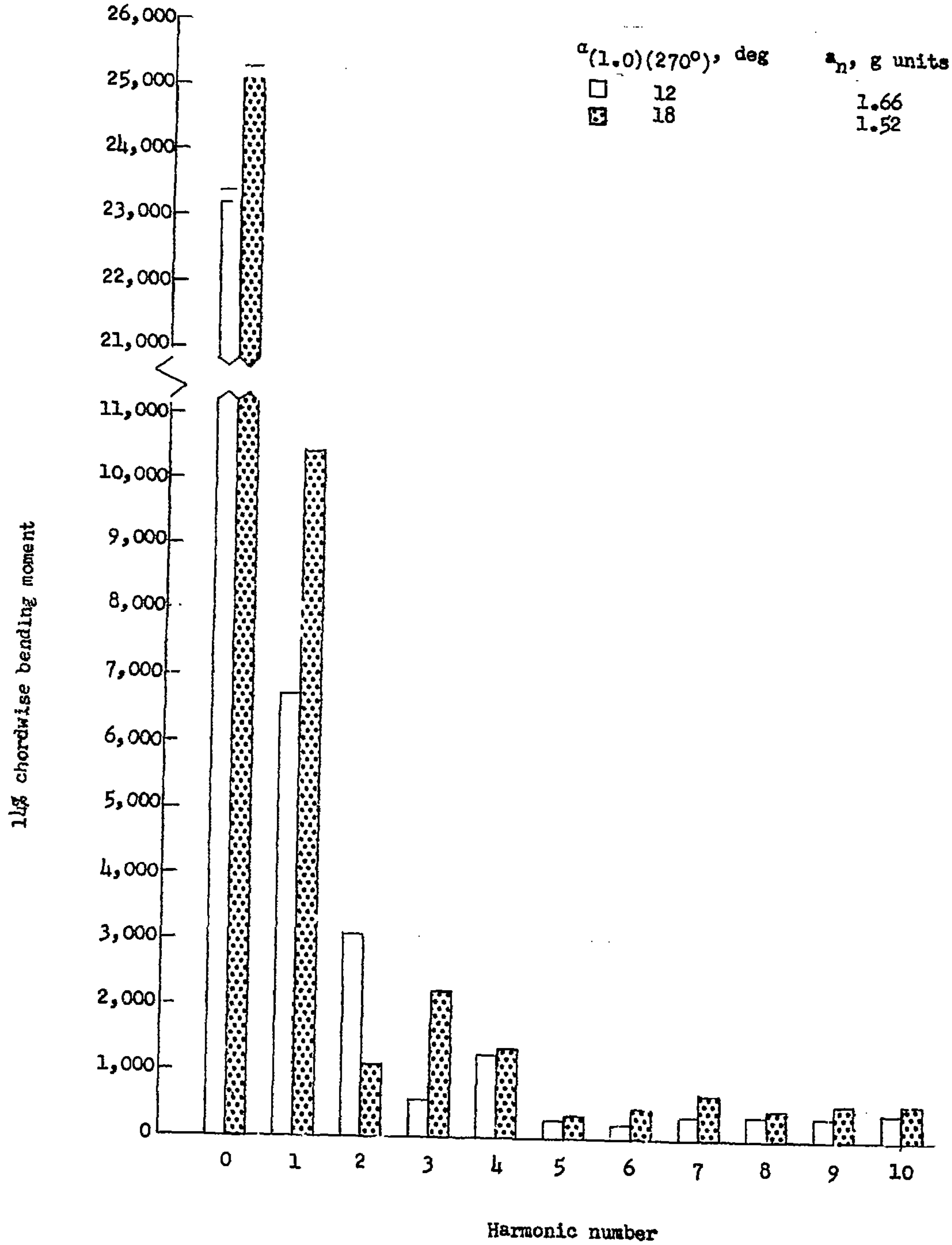


Figure 9.- Continued.

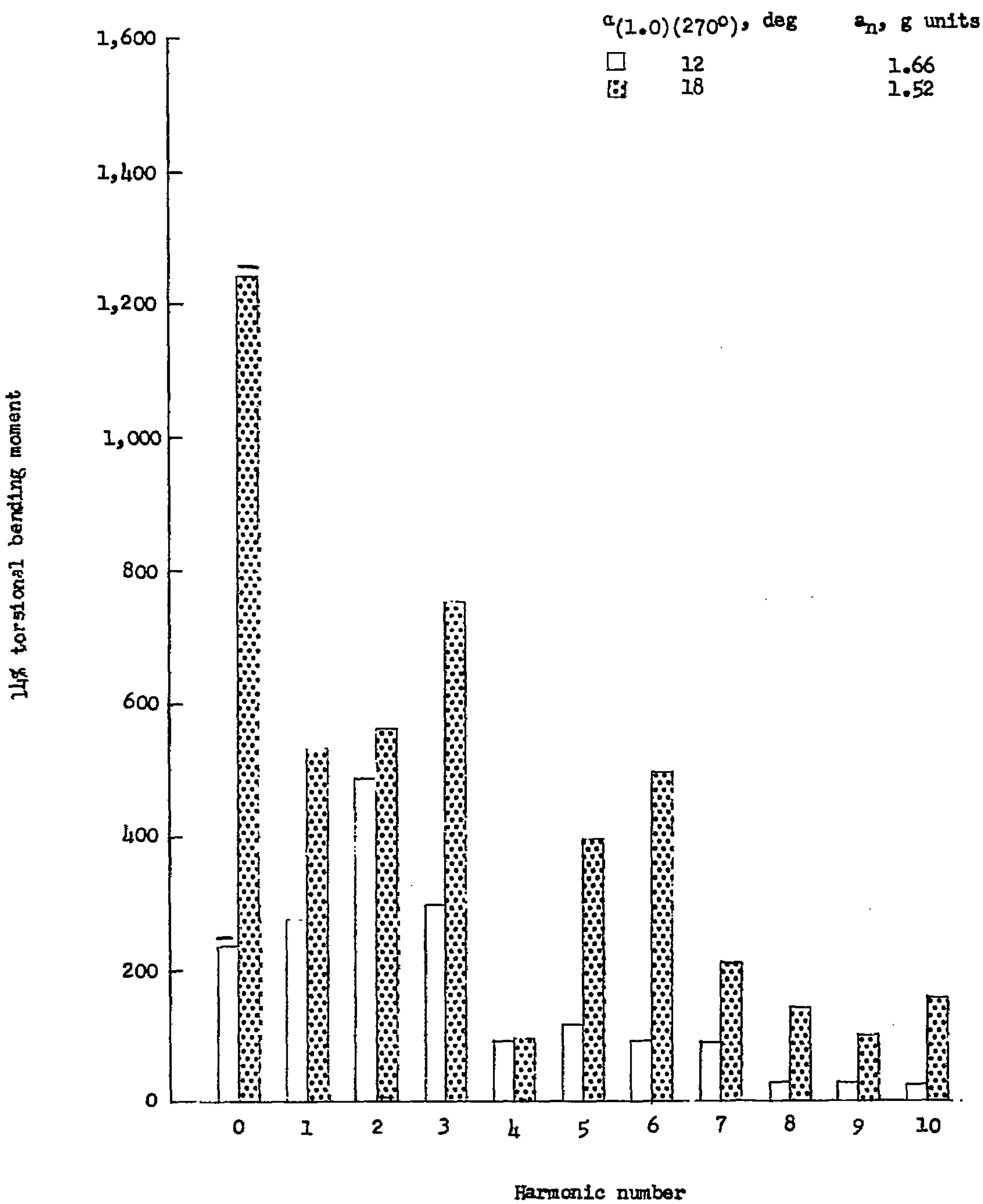


Figure 9.- Concluded.